Free-electron laser extreme ultraviolet lithography: considerations for high-volume manufacturing

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Extreme-Ultraviolet Lithography High-Volume Manufacturing

- **An EUV high-volume manufacturing (HVM) source has yet to be demonstrated**
- Will laser-produced plasma (LPP) execute to HVM powers, or is another source required?
  - Current EUVL tools are targeting 500 exposures per day at 15 mJ/cm^2
  - A mature HVM technology may require upwards of 50k wafers per month
  - 5-10 EUV layers at 7 nm node
  - Possible >50 mJ/cm^2 dose requirement
- Enter Free-Electron Lasers (FELs)
- LPP development and deployment must continue if EUVL is to enter HVM

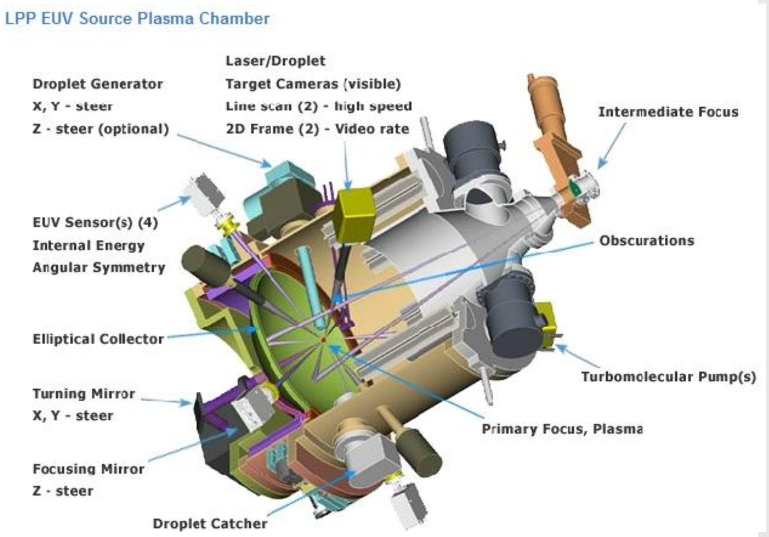
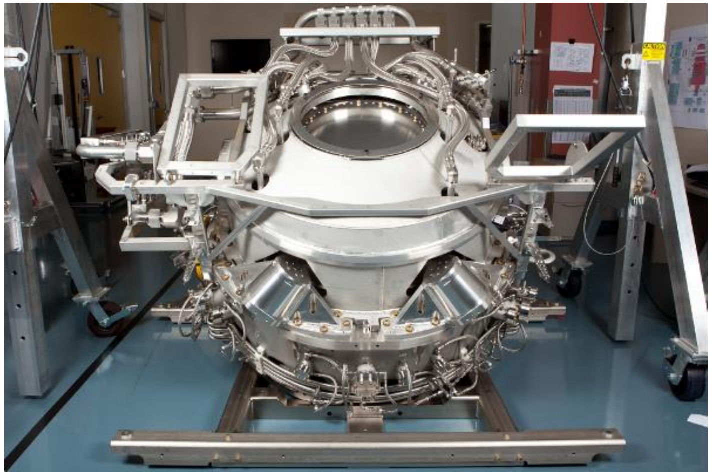
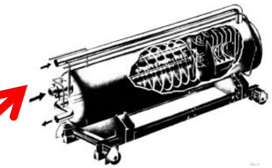


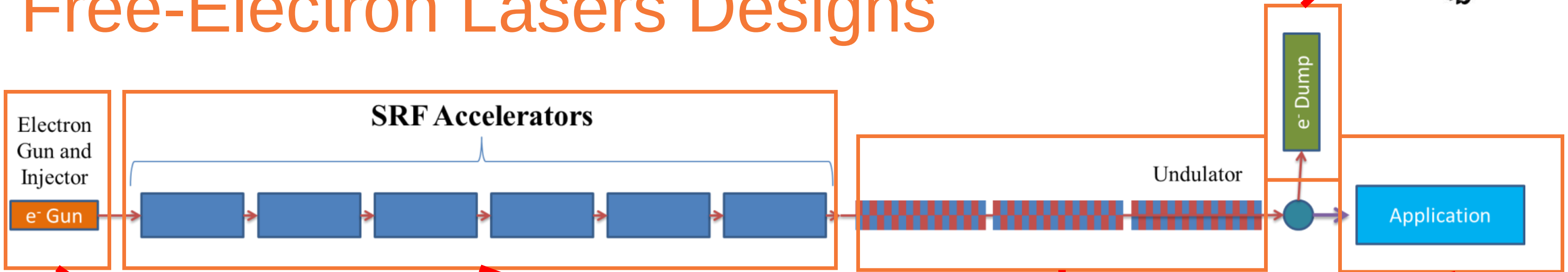
Photo Credits: Cymer



IMEC Technology Roadmap.
van Schoot., J., et al. EUVL 2014. Washington, D.C.

Free-Electron Lasers Designs





- FEL machine components:
  - **e$^-$ source/gun and injector**: generates and prepares e$^-$ bunch (overcome space charge effects)
  - **Linac (superconducting radio frequency (SRF) cavities)**: accelerates e$^-$ beam to relativistic speeds
  - **Undulator**: radiator, wiggles e$^-$ packet
  - **e$^-$ beam dump**: radiation source, must absorb enormous power
  - **End station**: EUV beam delivery and manipulation optics to multiple scanners
- Where can cost, efficiency, and reliability be optimized?
- Accomplished in Academia vs. Technologically Feasible

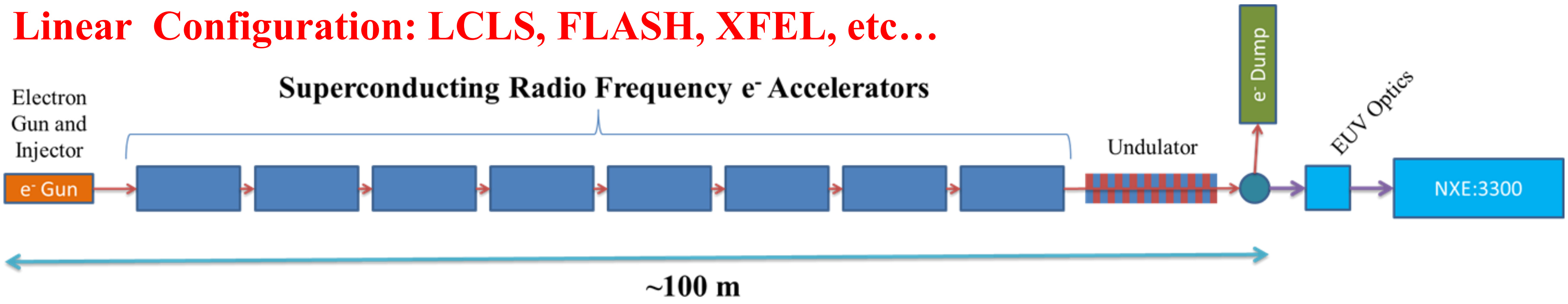
Diagrams courtesy of LBNL APEX Project, ILC, RIKEN, SLAC, ASML.

Lithographic Requirements

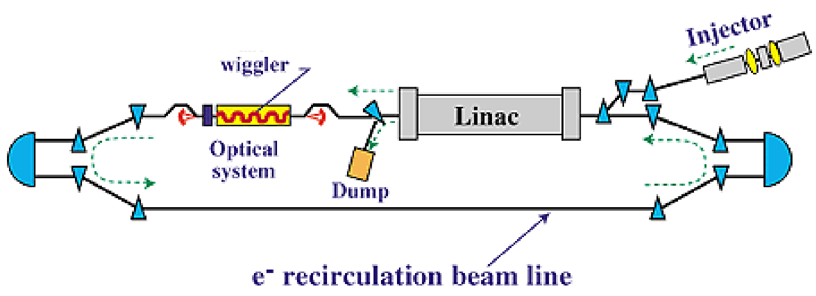
- An EUV FEL must power multiple scanners simultaneously
- **FEL EUV source must operate with an availability of 100%**
  - Redundancy of high-risk/low-cost machine components
  - Minimizing stress on long replacement time components
  - **Two FELs must be run simultaneously!**
- **Cost**
  - FEL EUV program must be substantially cheaper (depreciation + OpEx) and more powerful than an equivalent number of LPP sources to justify development risk
  - How many EUVL sources are required for HVM?
    - 7 nm Logic roadmap from IMEC says 5-10 EUV layers
    - 3-4 L/S (>25 mJ/cm^2), 2-6 contact (>35 mJ/cm^2) = 10x 250 W LPP tools for ~50k wafers/month
- Other: FEL Specific
  - Beam Distribution
    - High power, splitting efficiency
  - Power management and Facility Size
    - On mask, on mirrors, on wafer, into beam dump, and electrical power
    - Integrate with existing fab architecture
  - Coherence
    - Manipulate at scanner (Extended Flex-OAI?) or within distribution system
  - Harmonic mitigation scheme
    - FELs produce a few percent of the fundamental power in higher harmonics
  - Wavelength stability? Optical bandwidth? Power stability (Dose repro <0.2%)?

FEL Layout: Two Promising Configurations

Linear Configuration: LCLS, FLASH, XFEL, etc…



JLab IR Demo: Oscillator Multi-Pass Linac



Conducive to electron beam energy recovery.

Los Alamos Regenerative Amplifier FEL: RAFEL

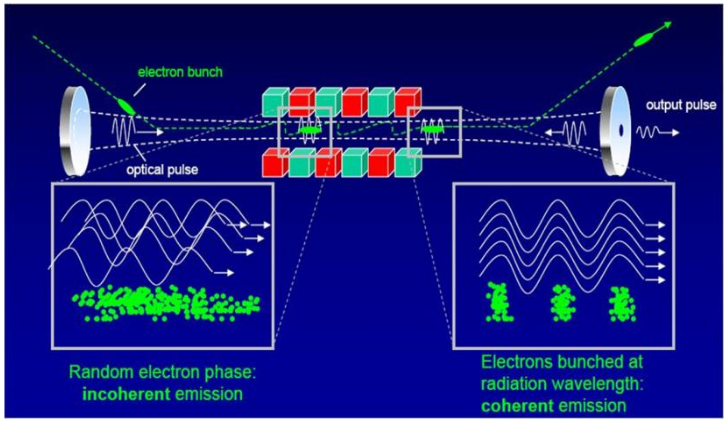


Diagram Credit: Jefferson Lab, Los Alamos, and USPAS

Cost of LPP vs. FEL for HVM

($M/year)		**250 W LPP Sources**	**10 kW EUV ERL FEL** (Scanners Powered @ 1 kW)
	OpEx	8.5[a]	23
	CapEx	25.6[b]	240
	Cost per Source, First Year[c]	34.1	263
Cost to Power 10 Scanners	**OpEx**	85	23
Cost to Power 10 Scanners	**CapEx**	256	240
Cost to Power 10 Scanners	**Total Cost First Year[c]**	>341	263
Cost to Power 10 Scanners	**FEL Savings Each Year[d]**		**>60**
	Uptime Per Source	Target 90%	**~100%**
	Average Exposures Per Day (10 Scanners, Dose: 25 mJ/cm^2)	13,280[e]	**29,700**

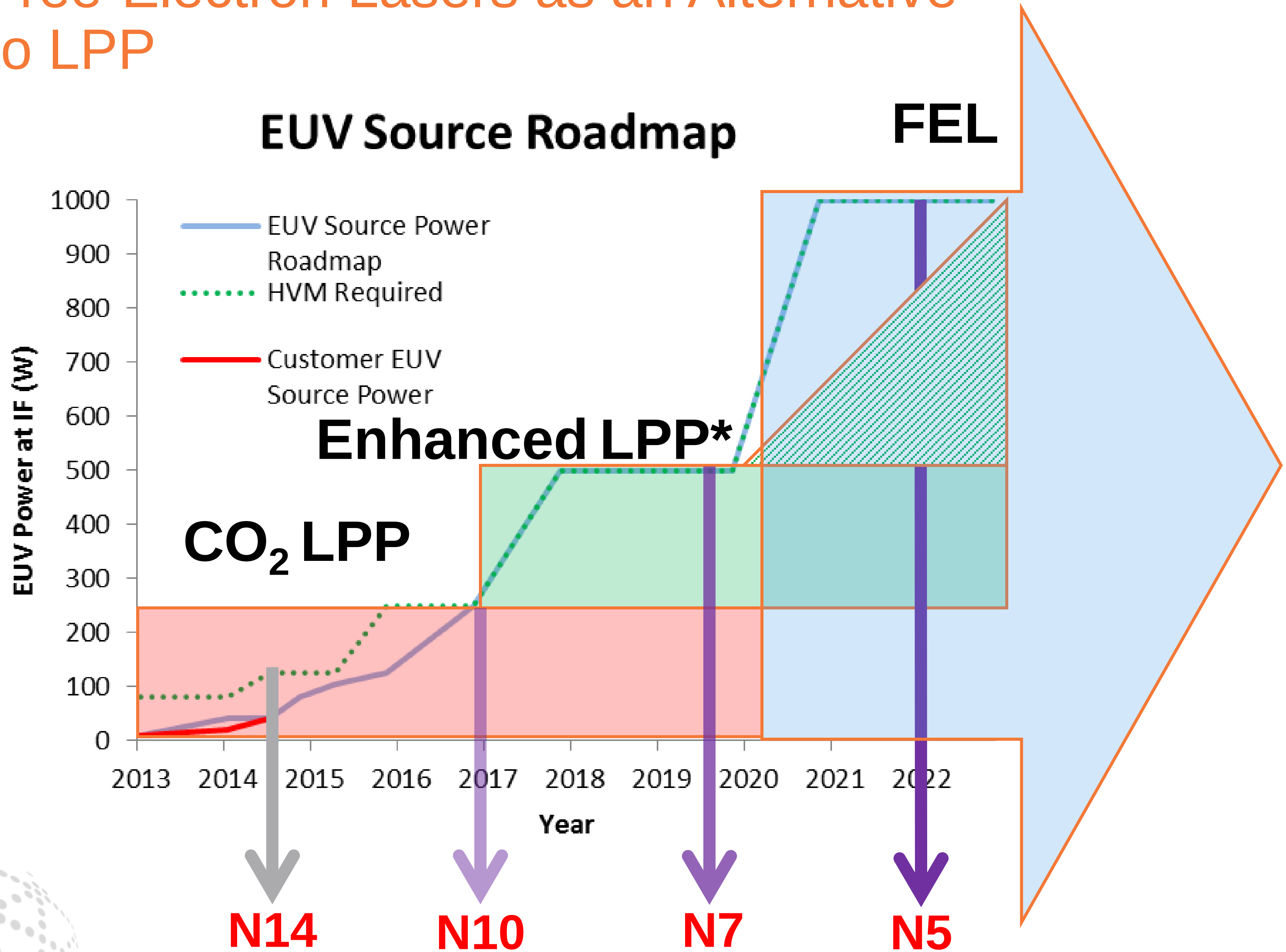
[a] LPP OpEx estimates from public source requirements and component lifetimes.
[b] LPP source (2013 configuration) cost from ABN AMRO Bank report on ASML: 8/21/2013.
[c] CapEx is fully depreciated in the first year to simplify projections.
[d] FEL savings are calculated after first year, once the sources are fully depreciated
[e] Calculation of throughput aligns with the current 500 WPD at 100% uptime, 15 mJ/cm^2 prediction.

FEL estimates represent a first level approximation of the cost associated with a recirculating Linac operating in a RAFEL mode. Estimates were developed from numerous technical design reports of existing and planned accelerators and free-electron laser facilities as well as quotes from various vendors (Linde, Radiabeam, and Kyma).

Interaction Between Customer and Integrator

- A vendor or large manufacturing entity will be need to act as the FEL facility integrator
  – Integrator will bring multiple independent sources together for FEL construction, previously, government labs held this role
  – Most FEL equipment has been commercialized:
    - undulator, vacuum equipment, RF systems, cryomodules, cryogenic plant
  – Specialized manufacturing will revolve around the FEL configuration and injector/electron gun assembly
  – Research Labs will provide key information regarding FEL construction and operation and will quite possibly play a critical role in daily FEL operation
    - Each customer site will bring its unique set or requirements and the first generation of machines after a demo will only be a few (x2 at each site though). FELs inherently lend themselves to flexible requirements.
  – ASML will need to ensure FEL integration with NXE tool series

Free-Electron Lasers as an Alternative to LPP



*Possibly YAG Pre-Pulse + CO_2 Main Pulse LPP or other innovations
Gigaphoton press release: http://optics.org/news/3/7/6
Nishihara, K., et al. EUVL 2008. Tahoe.
Reported EUV source powers and roadmap targets are from ASML/other public announcements.

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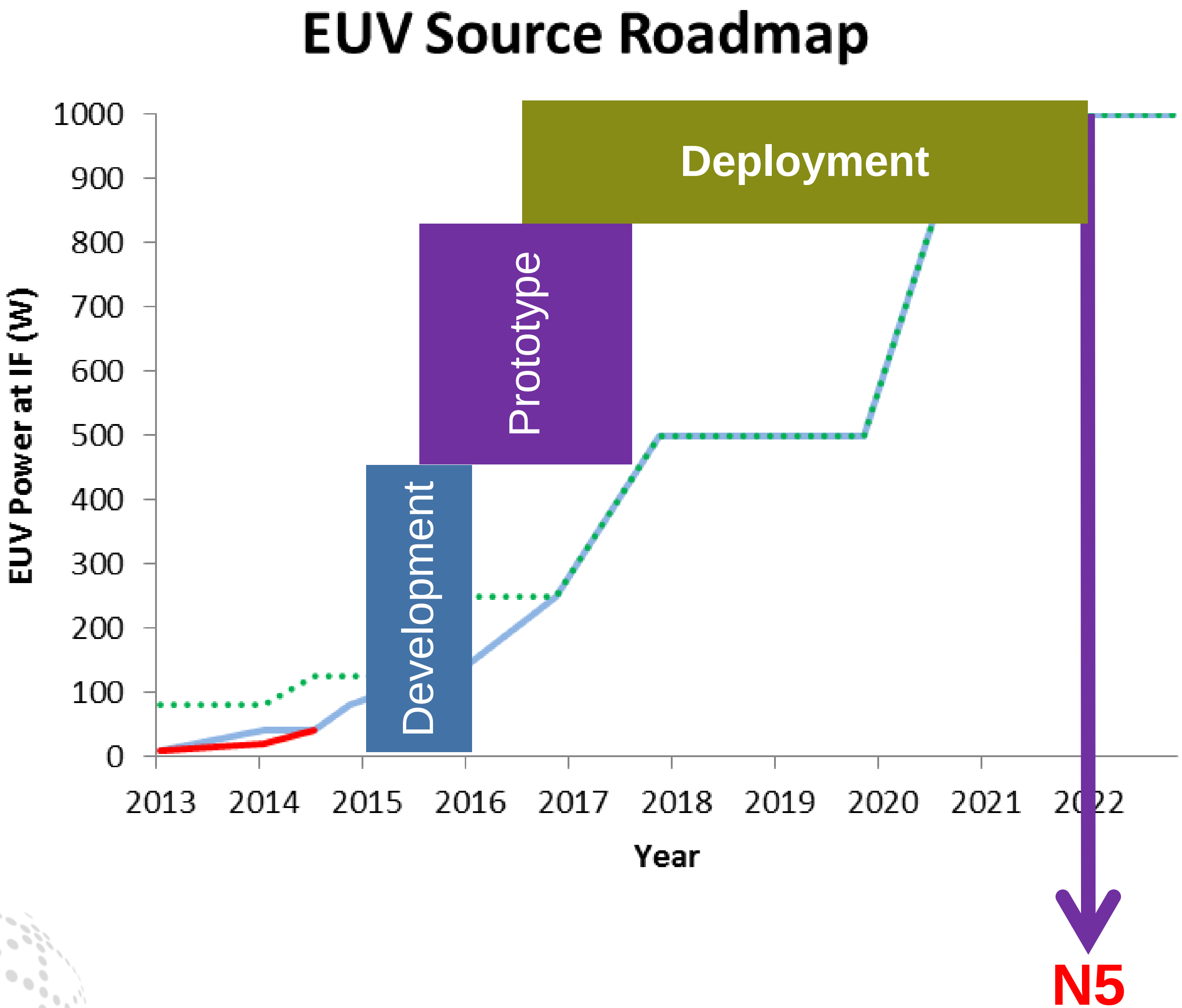

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Thank you

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